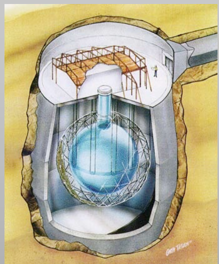
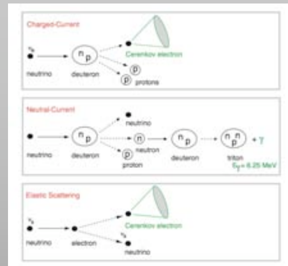
Neutrino Science at Berkeley Lab:
Understanding Neutrino Oscillations

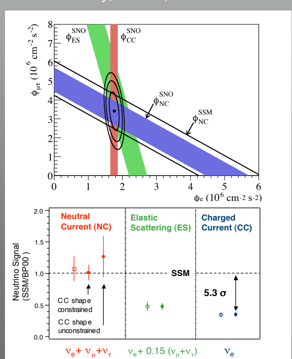
Model-Independent Evidence for the Flavor Change of Solar Neutrinos at SNO



The Sudbury Neutrino Observatory (SNO) is an imaging water Cherenkov detector located 2 km underground in the Creighton mine in Sudbury, Ontario, Canada.

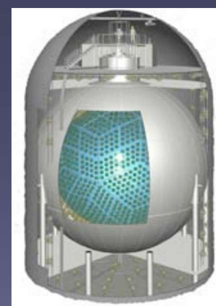


With 1000 tons of heavy water, SNO observes the interactions of solar ^{8}B neutrinos through 3 different interaction channels. Neutrino interactions with deuterium give SNO unique sensitive to all active neutrino flavors.



In 2002, SNO found that 2/3 of all solar electron neutrinos change their flavor *en route* to Earth and are detected as muon or tau neutrinos in the Sudbury Neutrino Observatory.

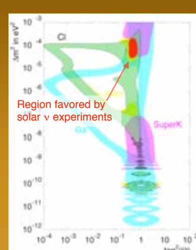
First Evidence for the Disappearance of Reactor Antineutrinos at KamLAND



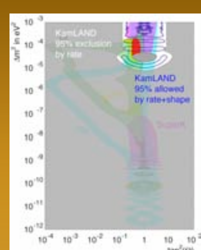
KamLAND (Kamioka Liquid Scintillator Anti-Neutrino Detector) is a 1-kton liquid scintillator detector in the Kamioka mine in central Japan designed to measure the antineutrino flux from nearby nuclear power plants. KamLAND detects reactor electron antineutrinos through inverse β-decay of $\bar{\nu}_e$ on protons.

KamLAND measured 61% of the expected antineutrino flux. In the 50-year history of reactor neutrino physics, KamLAND has found first evidence for the disappearance of reactor electron antineutrinos.

Evidence for Neutrino Oscillations

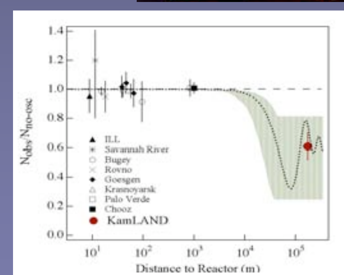


Before KamLAND
Solar neutrino experiments favor the 'Large-Mixing-Angle' oscillation solution.



After KamLAND
KamLAND's observation of $\bar{\nu}_e$ disappearance eliminates other oscillation solutions.

The observed flavor change of solar electron neutrinos in SNO and the measurement of antineutrino disappearance at KamLAND provide evidence for the oscillation of neutrinos (under the assumption of CPT invariance). KamLAND's result narrows the allowed neutrino oscillation parameters to the 'Large-Mixing-Angle' solution and strongly disfavors other possible mechanisms of neutrino flavor change.



Ratio of the measured $\bar{\nu}_e$ flux to the expected reactor $\bar{\nu}_e$ flux. The dashed line is the expectation for no neutrino oscillations. The dotted curve is representative of a best-fit 'Large-Mixing-Angle' oscillation solution.

Understanding the U_{MNS} Neutrino Mixing Matrix

Past, Present and Future Experiments

Results of the SNO solar neutrino experiment, the KamLAND reactor antineutrino experiment, and the evidence from the Super-Kamiokande atmospheric neutrino experiment have established the massive nature of neutrinos and point to a novel phenomenon called *neutrino oscillations*.

In the framework of neutrino oscillations the mass and flavor eigenstates of 3 active species are related through the U_{MNSP} matrix.

$$U=\begin{pmatrix}U_{e1}&U_{e2}&U_{e3}\\U_{\mu1}&U_{\mu2}&U_{\mu3}\\U_{\tau1}&U_{\tau2}&U_{\tau3}\end{pmatrix}$$

$$=\underbrace{\begin{pmatrix}1&0&0\\0&\cos\theta_{23}&\sin\theta_{23}\\0&-\sin\theta_{23}&\cos\theta_{23}\end{pmatrix}}_{\substack{\text{atmospheric }\nu\text{ present}\\\text{accelerator }\nu\text{ future}}}\times\overbrace{\underbrace{\begin{pmatrix}\cos\theta_{13}&0&e^{-i\delta_{CP}}\sin\theta_{13}\\0&1&0\\-e^{i\delta_{CP}}\sin\theta_{13}&0&\cos\theta_{13}\end{pmatrix}}_{\text{reactor and accelerator }\nu\text{ future}}}^{\text{Dirac phase}}\times\underbrace{\begin{pmatrix}\cos\theta_{12}&\sin\theta_{12}&0\\-\sin\theta_{12}&\cos\theta_{12}&0\\0&0&1\end{pmatrix}}_{\substack{\text{solar }\nu\text{ present}\\\text{solar }\nu\text{ future}}}\times\overbrace{\underbrace{\begin{pmatrix}1&0&0\\0&e^{i\alpha/2}&0\\0&0&e^{i\alpha/2+i\beta}\end{pmatrix}}_{0\nu\beta\beta\text{ experiments future}}}^{\text{Majorana phases}}$$

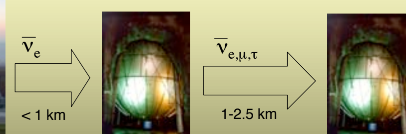
A variety of experiments are needed to determine all elements of the neutrino mixing matrix. The angle θ_{13} associated with the subdominant oscillation is still undetermined!

solar	$\theta_{12} = 33°$	*large*
atmospheric	$\theta_{23} = \sim 45°$	*maximal*
CHOOZ + SK	$\tan^2\theta_{13} < 0.03$ at 90% CL	*small … at best*

Future reactor neutrino experiments with multiple detectors have the opportunity to measure the last undetermined mixing angle θ_{13}. Knowing θ_{13} will be critical for establishing the feasibility of CP violation searches in the lepton sector.

Determining the Last Undetermined Mixing Angle: A Reactor Neutrino Experiment to Measure θ_{13}

With multiple detectors and a variable baseline a next-generation reactor neutrino experiment has the opportunity to discover sub-dominant neutrino oscillations and make a measurement of θ_{13}.



$$P_{ee} \approx 1-\sin^2 2\theta_{13}\sin^2\frac{\Delta m_{31}^2 L}{4E_\nu}-\cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\left(\frac{\Delta m_{21}^2 L}{4E_\nu}\right)$$

2-3 neutrino detectors with variable baseline

Diablo Canyon, California - An Ideal Site?

θ_{13} is central to neutrino oscillation physics

- Why are the mixing angles *large, maximal, and small*?
- Is there CP, T, or CPT violation in the lepton sector?
- Is there a connection between the lepton and the baryon sector?
- Understanding the role of neutrinos in the early Universe: Can leptogenesis explain the baryon asymmetry?

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